

Cold ultrarelativistic pulsar winds as potential sources of galactic gamma-ray lines above 100 GeV

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ABSTRACT

Context. The evidence of a line-like spectral features above 100 GeV, in particular at 130 GeV, recently reported from some parts of the galactic plane poses serious challenges for any interpretation of this surprise discovery. It is generally believed that the unusually narrow profile of the spectral line cannot be explained by conventional processes in astrophysical objects, and, if real, is likely to be associated with Dark Matter.

Aims. In this paper we argue that cold ultrarelativistic pulsar winds can be alternative sources of very narrow gamma-ray lines.

Methods. We demonstrate that Comptonization of a cold ultrarelativistic electron-positron pulsar wind in the deep Klein-Nishina regime can readily provide very narrow ($\Delta E/E \leq 0.2$) distinct gamma-ray line features. To verify this prediction, we produced photon count maps based on the Fermi LAT data in the energy interval 100 to 140 GeV.

Results. We confirm earlier reports of the presence of marginal gamma-ray line-like signals from three regions of the galactic plane. Although the maps show some structure inside these regions, unfortunately the limited photon statistics do not allow any firm conclusion in this regard.

Conclusions. The confirmation of 130 GeV line emission by low-energy threshold atmospheric Cherenkov telescope systems, in particular by the new 27 m diameter dish of the H.E.S.S. array, would be crucial for resolving the spatial structure of the reported hotspots, and thus for distinguishing between the Dark Matter and Pulsar origins of the ‘Fermi Lines’.

Key words. Keywords should be given

1. Introduction

Recent reports on the possible presence of a narrow line-like feature in the spectrum of gamma-ray emission at 130 GeV from the galactic center region, and, presumably, from some other parts of the galactic plane (Bringmann et al. 2012; Weniger 2012; Tempel et al. 2012; Boyarsky et al. 2012; Su & Finkbeiner 2012), have received a prompt and enthusiastic reaction from the astrophysics and particle physics communities. Despite the marginal statistical significance of the reported signals and some outstanding questions and inconsistencies, the implications of these results are hotly debated, basically in the context of Dark Matter (DM). This is motivated not only by the recognition of the potential of gamma-ray observations for indirect searches of DM (for a recent review see Bergström 2012) and the overall excitement caused by the possible association of the gamma-ray line at 130 GeV with DM (see e.g. Buckley & Hooper 2012), but also by unusual characteristics of the signal. It is generally believed that the width of the 130 GeV line (of a few tens of GeV) is too narrow to be explained by any physical process except for annihilation of DM¹. On the other

hand, some other features, in particular the significant shift of the center of gravity of the signal from the position of the galactic center (Su & Finkbeiner 2012), as well as the possible presence of gamma-ray lines at other energies (Boyarsky et al. 2012) and from other parts of the galactic plane (Tempel et al. 2012; Boyarsky et al. 2012), challenge the DM origin of the reported signal. Unfortunately, the marginal gamma-ray photon statistics does not allow definite conclusions in this regard. The situation will be somewhat improved after doubling the photon statistics above 100 GeV by observations of the galactic plane with *Fermi* Large Area Telescope (LAT) over the next several years. The development of new dedicated approaches to the data reduction focused on the highest energy domain of *Fermi* LAT also may help to clarify some of the current uncertainties and inconsistencies. Finally, there is hope that soon the low-energy threshold imaging Cherenkov telescopes, in particular the new 27m diameter dish of the H.E.S.S. telescope array located in the Southern Hemisphere (see <http://www.mpi-hd.mpg.de/hfm/HESS/>), will greatly contribute to the clarification of the question concerning

¹ Based on the analysis of *Fermi* LAT data by Weniger (2012), it has been argued (Profumo & Linden 2012) that the contamination of a bright featureless power-law background component (related e.g. to the radiation of the interstellar medium) by hard photons arriving from

Fermi bubbles with a sharp spectral break between 100 and 150 GeV, can mimic a spurious line. However, a closer look at the morphology shows that the 130 GeV feature is most likely not associated with Fermi Bubbles (see e.g. Tempel et al. 2012).

the origin of ≥ 100 GeV gamma-ray line(s) - are they *instrumental*, *cosmological* (DM), or *astrophysical*?

The last option implies production of gamma-rays by accelerated particles. So far it has been discarded, basically because of the common belief that conventional high energy processes with involvement of ultrarelativistic particles could not reproduce gamma-ray line features. In Sec.2 we briefly discuss different gamma-ray production mechanisms in the VHE domain in the context of their ability to produce sharp gamma-ray lines, and argue that the inverse Compton scattering in the Klein-Nishina regime by cold ultrarelativistic electron-positron pulsar winds can result in sharp gamma-ray line emission. The conditions for reproduction of narrow Klein-Nishina line profiles are discussed in Sec.3. Finally, in Sec.4 we describe our study of the spatial distribution of $E \geq 100$ GeV photons based on the *Fermi* LAT data. We confirm the results reported earlier on the presence of marginal gamma-ray line-like signals from three regions of the galactic plane, but, because of limited photon statistics, we cannot make a strong statement on the existence of localized hot spots inside the ‘Fermi Line’ regions. The results and conclusions are summarized in Sec.5.

2. Astrophysical VHE gamma-ray lines?

Interactions of relativistic particles with a broad energy distribution cannot result in sharp gamma-ray spectral features. Moreover, even in the case of interactions of monoenergetic relativistic particles, the energy spectra of resulting gamma-rays generally are broad. For example, a 1 TeV proton interacting with surrounding gas produces gamma-rays (through production and decay of π^0 -mesons) with an average energy of 100 GeV, but the distribution of gamma-rays is very broad with $\Delta E/E \gg 1$ (see e.g. Kelner et al. 2006). Actually, this is true for all hadronic interactions, including photomeson processes, with involvement of secondary π^0 -mesons.

Narrow gamma-ray distributions in principle can be expected from monoenergetic beams of ultrarelativistic heavy ions, e.g. ^{56}Fe , excited at interactions with surrounding low-frequency radiation. The Doppler-boosted gamma-ray emission due to the de-excitation of these nuclei with Lorentz factor $\Gamma \geq 10^5$ may lead, in principle, to a rather narrow lines at energy $E = \Gamma E^* \sim 100$ GeV (typically the prompt de-excitation gamma-ray lines are produced with energy in the frame of the nucleus $E^* \sim 1$ MeV). However, the efficiency of this mechanism in typical astrophysical environments is very low (Aharonian & Taylor 2010). Also, the disintegration of the primary nuclei would lead to emission of a large number of lines from secondary nuclei, and eventually to a rather broad distribution.

The synchrotron radiation of charged particles, electrons or protons, also leads to broad-band emission. Even in the case of radiation of monoenergetic particles in a homogeneous magnetic field, the spectral energy distribution (SED) is broad, $E^2 dN/dE \propto E^{4/3} \exp(-E/E_0)$ with $\Delta E/E \geq 1$. In addition to synchrotron radiation, there are two other processes for the production of high energy gamma-rays by relativistic electrons - bremsstrahlung and inverse Compton scattering (IC). Bremsstrahlung of monoenergetic electrons results in very hard, but still continuous gamma-ray distribution, $E^2 dN/dE \propto E$. One should mention also that at very high energies the electron cooling typically is dominated by synchrotron and IC radiation losses, thus bremsstrahlung plays an important role only at relatively low, sub-GeV energies.

In contrast, the inverse Compton scattering of relativistic electrons is a universal gamma-ray production mechanism which

can work with very high efficiency throughout the entire gamma-ray domain, from MeV to TeV energies, in diverse astrophysical environments, from compact objects like pulsars and AGN to extended sources like supernova remnants and clusters of galaxies (see e.g. Aharonian 2004). In the Thompson regime, IC scattering boosts the energy of target photons to $E_\gamma \propto \varepsilon \Gamma^2$, where ε is the target photon energy, and Γ is the electron Lorentz factor. Thus, in order to produce a narrow gamma-ray spectral feature, one should require very narrow distributions for both relativistic electrons and target photons. However, even in this case, the distribution of the upscattered radiation is relatively broad due to the character of the cross-section in the Thompson regime. Another principal limitation comes from the requirement of narrowness of the target photon field. Even in the case of black-body radiation, the width of the photon distribution exceeds the average photon energy $\varepsilon \approx 3$ kT, thus the original distribution of target photons will be shifted to higher energies by a factor of Γ^2 , and non-negligibly broaden due to the cross-section in the Thompson regime. Even in the case of an abrupt cutoff in the electron spectrum and the Planckian distribution of target photons, the spectrum of gamma-rays contains a rather long exponential tail (Lefa et al. 2012).

The picture changes dramatically, however, when the IC scattering proceeds in the Klein-Nishina regime, i.e. when $b = \varepsilon E_e/m_e^2 c^4 \geq 1$. In this case, the target photons take the entire momentum of the electron, thus, independent of the energy distribution of target photons, one may expect a line shape for the upscattered radiation if the electrons have a very narrow distribution. Both conditions can be realized in pulsars, namely when the cold ultrarelativistic electron-positron pulsar winds upscatter the surrounding high energy gamma-ray emission (Bogovalov & Aharonian 2000). For isolated pulsars, a sharp gamma-ray line is produced at Comptonization of the electron-positron wind by the thermal X-ray emission from the surface of the neutron star. The mechanism can be effective only if the conversion of the Poynting flux to kinetic energy of the bulk motion (“acceleration” of the wind) takes place close to the light cylinder (Bogovalov & Aharonian 2000). In the case of pulsars with bright nonthermal broad-band magnetospheric emission, e.g. in the Crab pulsar, the major fraction of energy of the wind is channelled into the pulsed VHE continuum. It is likely (Aharonian et al. 2012) that this component of radiation of the pulsar wind is responsible for the recently detected VHE pulsed radiation of the Crab pulsar (VERITAS Collaboration et al. 2011; Aleksić et al. 2012).

Gamma-ray line-like structures are expected also from binary systems containing a pulsar and a luminous optical star (Ball & Kirk 2000; Khangulyan et al. 2007). In this case the efficiency of IC scattering is higher because of presence of copious target photons provided by the companion star, but the gamma-ray lines are less sharp compared to the isolated pulsars because of smaller values of the Klein-Nishina parameter b . It has been recently argued (Khangulyan et al. 2012) that the bright flare of the binary pulsar PSR 1259-63/LS2883, detected by *Fermi* in 2011 (Abdo et al. 2011; Tam et al. 2011), could be best explained by the IC scattering of the unshocked pulsar. The spectral measurements of *Fermi* LAT require a relatively modest Lorentz factor of the wind, $\Gamma \approx 10^4$; the IC scattering proceeds in the Thompson regime, therefore the resulting gamma-radiation has a rather broad energy distribution (Khangulyan et al. 2012).

Finally, one should mention two other (highly speculative) scenarios of formation of a very narrow multi-GeV spectral gamma-ray line feature. It could be related to the 0.511 MeV line produced at annihilation of (e^+e^-) pairs in cold plasma of an

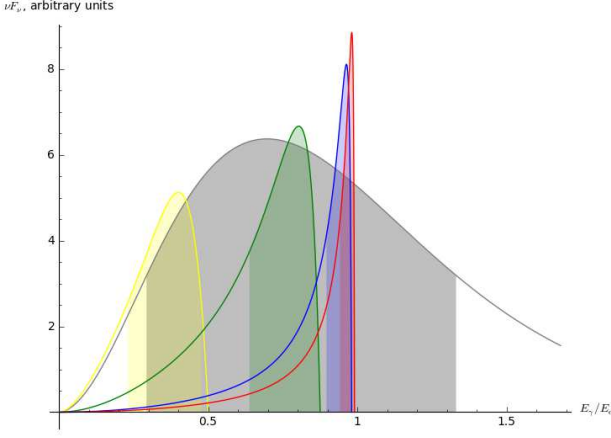


Fig. 1. *Colour:* energy spectra of the inverse Compton radiation of mono-energetic electrons upscattering isotropic target photons for 4 different values of the parameter b : 1, 7, 50 and 100. The energy of gamma-rays is in units of the electron energy. *Grey:* the gamma-ray spectrum produced by electrons with relativistic Maxwellian distribution; in this case the photon energies are in units of 4Θ , where Θ is the “temperature” of Maxwellian distribution.

outflow (jet or a wind) relativistically moving with Lorentz factor $\Gamma \geq 10^4$. A very sharp increase of the gamma-ray spectrum can be expected also in a quite different scenario - due to the process of photon-photon absorption in optically thick gamma-ray sources.

3. Formation of sharp Klein-Nishina lines

The strongest argument in favor of non-astrophysical origin of the ~ 130 GeV spectral feature is its very sharp profile. It is very narrow, $\Delta E/E \approx \frac{20 \text{ GeV}}{130 \text{ GeV}} \approx 15\%$, with an exponential rise and decay of the flux (which correspond to linear dependence as seen in the semi-logarithmic scale plots), while in typical astrophysical situations we expect much smoother spectral distributions. Nevertheless, in the case of inverse Compton scattering such profiles can be reproduced by monoenergetic electrons provided that the scattering proceeds in deep Klein-Nishina regime. In this case the shape of the radiation spectrum is fully determined by a single parameter, $b = 4\omega\Gamma$, where $\omega = \varepsilon/m_e c^2$ and $\Gamma = E_e/m_e c^2$ are the energy of the target photon in $m_e c^2$ units and the electron Lorentz factor, respectively. In Fig. 1 IC gamma-ray spectra are shown calculated for four different values of the parameter b : 1, 7, 50 and 100. The filled regions below each line correspond to the intervals where the flux level exceeds 50% of the maximum value. Since the reported gamma-ray line flux is above the background only by a factor of two, for characterization of the line profile we use the *half-height width* as a measure of the line thickness. This also allows us to define the hardness of the left wing of the line by the power-law slope at the point where the flux level reaches 50% of the maximum value (the lower energy point). The line thickness and hardness determined in this way are shown in Fig. 2 as functions of the parameter b .

In the Klein-Nishina regime, the upscattered photons repeat, to a large extent, the spectrum of parent electrons. Therefore even the Maxwellian distribution of electrons, which is generally considered as a *very narrow* one in the context of particle acceleration scenarios, and which can be realized only with very specific conditions, cannot explain the reported very nar-

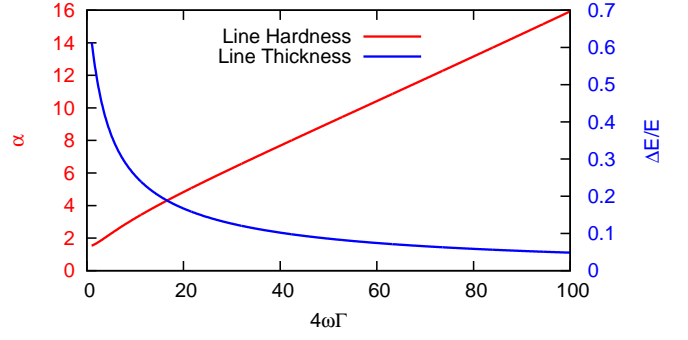


Fig. 2. The thickness and hardness of the Klein-Nishina line as functions of the b -parameter.

row line. This is illustrated in Fig. 1, where the IC gamma-ray spectrum produced by electrons with a Maxwellian distribution, $dN_e/d\Gamma \propto \Gamma^2 \exp(-\Gamma/\Theta)$ is shown; the energy of gamma rays are expressed in units of 4Θ , where Θ is the electron “temperature”. It can be seen that the half-height width of this spectrum is comparable to the energy at which the distribution maximum is achieved at $E_\gamma \sim 2.8\Theta$, and thus much broader than the observed one. Meanwhile, the results presented in Fig. 1 show that the monoenergetic distribution of electrons does provide very sharp feature at $E_\gamma = E_e$ with a width $\Delta E/E \leq 15\%$, provided that the Klein-Nishina parameter $b \geq 30$. The corresponding hardness of the line, $\alpha = 6$, also is in good agreement with observations. Note that the fixed value of the parameter b implies a monoenergetic distribution of target photons. Although in specific calculations one should assume more realistic spectrum of seed photons, this cannot significantly change the conclusions as long the parameter b remains large. Given that for $b \gg 1$, with a good accuracy $E_\gamma = E_e$, one can immediately constrain the energy range of target photons.

$$\varepsilon \geq 15(E_\gamma/130 \text{ GeV})^{-1} \text{ eV}, \quad (1)$$

where E_γ is the energy of the detected line. In the case of Planckian radiation field, the above photon energy corresponds approximately to the radiation temperature of $\sim 5 \times 10^4$ K. In the case of isolated pulsars, thermal emission from the surface of the neutron star would be the main source of seed photons for the formation of gamma-ray lines. The neutron star’s surface temperature exceeds by two orders of magnitude this limit, thus from isolated pulsars we may expect extremely narrow gamma-ray lines. In binary systems with pulsars, the seed photons are provided by companion stars with radiation temperatures slightly less than the above estimate. Correspondingly, the gamma-ray lines would be broader with $\Delta E/E \geq 20\%$; this still marginally agrees with observations of the 130 GeV line from the galactic center region. On the other hand, the efficiency of formation of Klein-Nishina lines from pulsar winds in binary systems is significantly higher in binary systems than in isolated pulsars.

4. Structure of gamma-ray line ‘hotspots’

An astrophysical origin of the 130 GeV line in general, and, more specifically, its association with pulsars, would imply that the extended regions of excess emission are not truly diffuse structures, but rather represent superpositions of multiple unresolved discrete gamma-ray sources. In order to verify this hypothesis we analyzed 52 month data of *Fermi*/LAT using the latest *Fermi* software package v9r27p1. The LAT aboard the *Fermi*

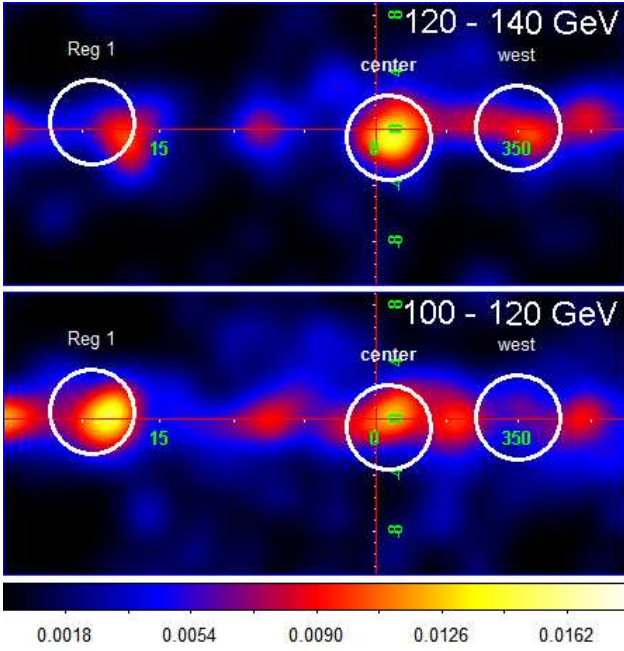


Fig. 3. The count maps of the “Central”, “West” and *Reg 1* regions (see the text) in two energy intervals, 100-120 TeV and 120-140 TeV, smoothed with 3° FWHM gaussian kernel

Region	Hot spot	l	b	R, deg	TS
Central		359.0	-0.7	3	
	2FGL J1745.6-2858	359.97	-0.04	0.02	8.5
	2FGL J1740.4-3054c	357.73	-0.08	0.16	8.4
	c1	359.02	-1.41	0.08	7.5
	c2	358.45	-1.08	0.12	9.2
West	c3	358.43	1.47	0.23	8.6
	w1	349.55	-0.57	0.19	6.9
Reg 1		19.38	0.40	3	

Table 1. The coordinates and names of considered regions and point-like hot spots detected in these regions. l and b are galactic coordinates of the region (new source), R – the radius of the region (the radius of error-circle of the source). TS is the test-statistical value of the point-like hot spot (if > 5). The significance of the hot spot can be estimated as $\sqrt{TS}\sigma$, see e.g. Mattox et al. (1996)

satellite is a pair-conversion gamma-ray detector operating between 20 MeV and 300 GeV. The *Fermi* LAT has a wide field of view of ~ 2.4 sr at 1 GeV, and observes the entire sky every two orbits. The details on this instrument can be found in Atwood et al. (2009).

Here we consider three regions from which excess gamma-ray lines have been reported (Tempel et al. 2012; Su & Finkbeiner 2012; Boyarsky et al. 2012) in the energy interval between 100-140 GeV. The results are presented in Figs. 3 and 4, and summarized in Table 1.

In Fig. 3 we show the count maps smoothed with 3° FWHM Gaussian kernel in two energy intervals, 100-120 GeV and 120-140 GeV. They are consistent with the previously reported results. The locations of the “Central” and “West” regions with excess emission at 120-140 GeV (Tempel et al. 2012) and the “Reg 1” region with the excess emission at 100-120 GeV (Boyarsky et al. 2012), are shown with white circles.

In order to explore the spatial structures of these regions we produced corresponding count maps smoothed with 0.25° gaussian kernel (comparable to the *Fermi* PSF at 100 GeV). The corresponding maps are shown in Fig. 4. The regions from Tempel et al. (2012) and Boyarsky et al. (2012) are shown with white circles. The green crosses show positions of some of the GeV gamma-ray sources from the *Fermi* two-year source catalog.

In the “Central” region, one can see several “hot spots” (see Table 1 for the coordinates and the test statistical (TS) values of these “hot spots” with $TS \geq 5$), however the photon statistics in each of them is limited. The number of photons in five “hot spots” is 16 (from 32 total photons in the region), and the residual flux after removing the excesses is comparable with the background (see e.g. Boyarsky et al. (2012)). Thus, the tendency of clumped distribution of photons inside the “Central” region can be taken only as a hint for presence of discrete sources of VHE gamma-rays. It is interesting to note that the chance of false-positive detection for the two brightest clumps (7 photons in total) over the uniform photon distribution is about 7%. Their possible association with two hypothetical pulsars seems a quite intriguing option in the context of interpretation of the possible two-peak structure of the 130 GeV line (Su & Finkbeiner 2012) as a superposition of Klein-Nishina lines from two pulsar winds with different Lorentz factors. The search for candidate pulsars at these positions would be a straightforward test for verification of this hypothesis, although the detection of pulsars through their magnetospheric emission cannot be guaranteed because of possible misorientations of their radiation cones.

The “West” (at 120-140 GeV) and “Reg 1” (at 100-120 GeV) regions looks more diffuse in gamma-rays (see Fig. 4, middle and right panels), however the poor photon statistics do not allow any conclusion concerning the level of clumpiness in these regions. While for confirmation of gamma-ray line signals from these regions an increase of photon statistics by a factor of two or three would be adequate, the study of spatial distributions of gamma-rays inside these regions is a more demanding task and requires much higher photon statistics.

5. Summary

In this paper we argue that there is a viable alternative to the DM origin of the 130 GeV gamma-ray line as recently reported to be present in the galactic gamma-ray emission. We demonstrate that very sharp gamma-ray spectral lines can be produced by pulsar winds through their Comptonization, predominantly by energetic (UV, X-ray) radiation with a relatively narrow spectral distribution, thus the IC scattering proceeds in the deep Klein-Nishina limit. In principle, these conditions can be fulfilled both in isolated pulsars and binary systems. The current paradigm which connects pulsars with their synchrotron nebulae through cold ultrarelativistic electron-positron winds, postulates that the electron-positron wind with a Lorentz factor between 10^4 to 10^6 , carries away almost the entire rotational energy lost by the pulsar. Thus, under the condition of effective Comptonization of the wind, a substantial fraction of the spin-down luminosity of a pulsar L_{tot} can be released in a single gamma-ray line. Depending on the intensity of illumination of the pulsar wind by surrounding radiation field(s), the efficiency of formation of such lines can be very high, formally close to 100 %. Interestingly, the narrow profile of the 130 GeV line argues against such an extreme efficiency which can be realized in the case of optically thick source; this would imply not only strong attenuation of gamma-rays due to photon-photon pair production, but also sig-

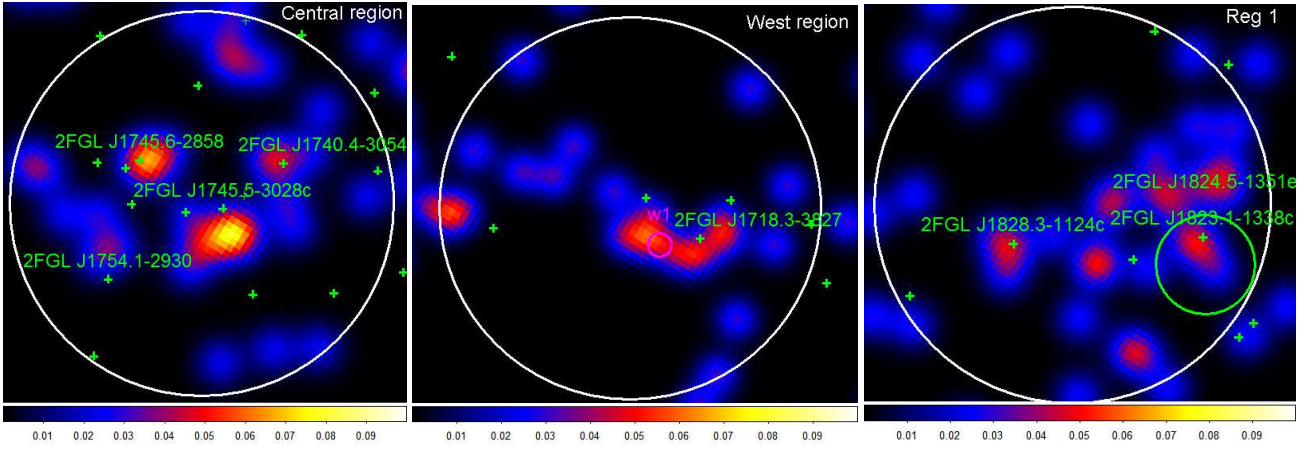


Fig. 4. Photon count maps of the “Central” (left) and “West” (middle) regions at 120–140 GeV and the “Reg 1” region at 100–120 GeV energy bands smoothed with 0.25° gaussian kernel ($\approx 95\%$ *Fermi* PSF at 100 GeV). The corresponding regions from Tempel et al. (2012); Boyarsky et al. (2012) are shown with white circles, while the sources from the *Fermi* LAT two-year catalog are shown with green crosses.

nificant broadening of the line because of the cooling of electrons. However, both effects become negligible in the case of still very high, $\leq 10 - 20\%$ efficiency of the wind Comptonization. Conservative estimates show that while such an efficiency can be readily achieved in binary systems, in the case of isolated pulsars the efficiency is expected to be very low unless the acceleration of the wind takes place close to the light cylinder. The efficiency of transformation of kinetic energy of the pulsar wind into Klein-Nishina gamma-ray lines is a key issue the discussion of which is beyond the scope of this paper. Clearly, under certain conditions, the efficiency can be quite high, and, for pulsars with spin-down luminosities exceeding 10^{36} erg/s and wind Lorentz factor $\geq 2 \times 10^5$, one may expect ≥ 100 GeV gamma-ray lines with luminosities exceeding the bolometric luminosities of magnetospheric emission of pulsars. Moreover, one cannot exclude other configurations of compact objects, e.g. magnetars, with (hypothetical) relativistic electron-positron winds, as effective multi-GeV gamma-ray emitters.

In this regard a natural question arises: if the pulsars can work as effective generators of VHE gamma-ray lines, why have they not been detected yet? There could be several answers to this question. In particular, in many objects the target radiation field could not be sufficient for effective conversion of the kinetic energy of the wind to IC gamma-radiation. Alternatively, if the wind Lorentz factor is small and/or the target photons have a broad distribution, the IC scattering of electrons in the Thompson regime would lead to a gamma-ray continuum the detection and identification of which could appear not an easy task. The formation of the line is effective only for pulsars with wind Lorentz factor exceeding 10^5 ; the corresponding gamma-ray line is formed around or above 100 GeV. At these energies the potential of *Fermi* LAT is limited because of the small detection area. On the other hand, the current imaging Cherenkov telescopes operate effectively above 100 GeV, so could simply have missed the lines around 100 GeV. Over the next several years *Fermi* LAT can double the photon statistics which will be sufficient, hopefully, for a firm detection of the 130 GeV line, but still not adequate for morphological studies of the gamma-ray line emitting regions. In this regard more promising seem to be forthcoming studies with new, low-energy threshold imaging atmospheric Cherenkov telescope systems, in particular by the new 27 m diameter dish of the H.E.S.S. telescope array which

is located in a perfect site in the Southern Hemisphere for observations of the galactic center region. This new instrument with energy threshold as low as 50 GeV, huge collection area exceeding 10^4 m², and energy resolution close to 20 % should allow (in the near future!) deep spectroscopic and morphological studies of the inner galaxy in multi-GeV gamma-ray lines. If confirmed, the existence of such lines may lead to an exciting new research area – *Klein-Nishina gamma-ray line astronomy* – that will open the way for future ground-based gamma-ray detectors, in particular the Cherenkov Telescope Array (see <http://www.cta-observatory.org/>) to probe the physics and astrophysics of relativistic outflows, in particular pulsar winds.

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